

Ψ and Υ Production in p-p Collisions at E=5, 14 TeV; and Comparison With Experiment at E= 7 TeV

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Abstract

This brief report is an extension of our recent studies of Ψ and Υ production cross sections in proton-proton collisions with $E=\sqrt{s}=13$ TeV to $E=5$ and $E=14$ TeV, using the mixed heavy quark hybrid theory in which the $\Psi(2S)$ and $\Upsilon(3S)$ are 50% hybrid states. Also, comparison with recent experiments at $E=7$ TeV are used to test the mixed heavy hybrid theory.

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1 Introduction

The present work is motivated by experiments at the LHC with Energy(E)=5 TeV and data collected in 2015[1], and 14 TeV, which might be carried out in the future. It is an extension of our recent study of Ψ and Υ production via p-p Collisions at $\sqrt{s}=E=13$ TeV[2]. We use the theory described in detail in Ref[3] based on the octet model[4, 5, 6] for p-p production of heavy quark states, and the heavy quark hybrid theory[7] with the $\Psi(2S)$ and $\Upsilon(3S)$ states a 50%-50% mixture of standard quarkonium and hybrid quarkonium states. The hybrid component has active gluons, which enhances the production of $\Psi(2S)$ and $\Upsilon(3S)$ compared to the standard model[3].

The differential rapidity cross section for the $J/\Psi(1S)$ or $\Upsilon(1S)$ meson production for the helicity $\lambda = 0$, with $\Phi = J/\Psi(1S)$ or $\Upsilon(1S)$ is given by [3].

$$\frac{d\sigma_{pp \rightarrow \Phi(\lambda=0)}}{dy} = A_{\Phi} \frac{1}{x(y)} f_g(x(y), 2m) f_g(a/x(y), 2m) \frac{dx}{dy}, \quad (1)$$

where y =rapidity, $a = 4m^2/s$, $s = E^2$, $A_{\Phi} = \frac{5\pi^3\alpha_s^2}{288m^3s} < O_8^{\Phi}(^1S_0) >$, with $\alpha_s=.118$, $< O_8^{\Phi}(^1S_0) >=.0087 GeV^3$, and f_g is the gluonic distribution function. In the present work $E = \sqrt{s} = 5.0$ and 14.0 TeV. For $J/\Psi, \Psi(2S)$ production $m \simeq 1.5$ GeV, and for $\Upsilon(nS)$ production $m \simeq 5.0$ GeV.

The functions $x(y)$ and $\frac{dx}{dy}$ of the rapidity variable y are

$$\begin{aligned} x(y) &= 0.5 \left[\frac{m}{E}(\exp y - \exp(-y)) + \sqrt{\left(\frac{m}{E}(\exp y - \exp(-y))\right)^2 + 4a} \right] \\ \frac{dx(y)}{dy} &= \frac{m}{2E}(\exp y + \exp(-y)) \left[1 + \frac{\frac{m}{E}(\exp y - \exp(-y))}{\sqrt{\left(\frac{m}{E}(\exp y - \exp(-y))\right)^2 + 4a}} \right]. \end{aligned} \quad (2)$$

The gluonic distribution $f_g(x(y), 2m)$ for the range of x needed for both $E = 5.0$ and $E = 14.0$ TeV is [3]

$$f_g(x(y)) = 1334.21 - 67056.5 * x(y) + 887962.0 * x(y)^2. \quad (3)$$

Using the method of QCD sum rules it was shown [7] that the $\Psi(2S)$ and $\Upsilon(3S)$ states are a 50%-50% mixture (with approximately a 10% uncertainty) of standard quarkonium and hybrid quarkonium states. Thus the $\Psi(2S)$ state is

$$|\Psi(2S) > = -0.7|c\bar{c}(2S) > + \sqrt{1-0.5}|c\bar{c}g(2S) >, \quad (4)$$

and the $\Upsilon(3S)$ state is

$$|\Upsilon(3S) > = -0.7|b\bar{b}(3S) > + \sqrt{1-0.5}|b\bar{b}g(3S) >, \quad (5)$$

with c a charm quark and b a bottom quark. Also in Ref [7] it was shown the $J/\Psi(1S)$ is essentially a standard $c\bar{c}$ state, and the $\Upsilon(1S)$, $\Upsilon(2S)$ are standard $b\bar{b}$ states.

2 Differential Rapidity Cross Sections for $J/\Psi, \Psi(2S), \Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ Production Via p-p Collisions at E= 5 TeV

For $J/\Psi(1S)$ production at 5 TeV $a \simeq 3.6 \times 10^{-7}$ and $A_{\Psi(1S)} \simeq 1.25 \times 10^{-6}$ nb. For $\Psi(2S)$ production with the standard model $A_{\Psi(2S)} \simeq 0.039A_{\Psi(1S)}$, while with the mixed hybrid theory $A_{\Psi(2S)} \simeq 0.122A_{\Psi(1S)}$.

For Υ production at 5 TeV $a \simeq 4.0 \times 10^{-6}$ and $A_{\Upsilon(1S)} \simeq 1.3 \times 10^{-8}$, while $A_{\Upsilon(2S)} \simeq 0.039A_{\Upsilon(1S)}$, $A_{\Upsilon(3S)} \simeq 0.0064A_{\Upsilon(1S)}$ for the standard model, and $A_{\Upsilon(3S)} \simeq 0.02A_{\Upsilon(1S)}$ for the mixed hybrid theory.

With the parameters given above for $J/\Psi(1S)$ and $\Psi(2S)$ production, from Eq(1), $d\sigma_{pp \rightarrow \Psi(1S)}/dy$, and $d\sigma_{pp \rightarrow \Psi(2S)}/dy$ both for the standard model and the mixed hybrid theory for the $\Psi(2S)$ state are shown in Figure 1.

Similarly, with the parameters given above for Υ production, with the standard model for $\Upsilon(1S)$ and $\Upsilon(2S)$ and both the standard and mixed hybrid theory for $\Upsilon(3S)$, the differential rapidity cross sections for Υ production are shown in Figure 2.

Note that $d\sigma_{pp \rightarrow \Psi(2S-\text{standard})}/dy$ is much smaller than $d\sigma_{pp \rightarrow \Psi(2S-\text{hybrid})}/dy$, and that $d\sigma_{pp \rightarrow \Upsilon(3S-\text{standard})}/dy$ is much smaller than $d\sigma_{pp \rightarrow \Upsilon(3S-\text{hybrid})}/dy$. This is important for studies of the possible production of the Quark Gluon Plasma (QGP) in Relativistic High Energy Collisions (RHIC). See, e.g., Ref [8].

The differential rapidity cross sections for $J/\Psi(1S)$ and $\Psi(2S)$ production for the standard model and the mixed hybrid theory for $E=5$ TeV are shown in Figure 1.

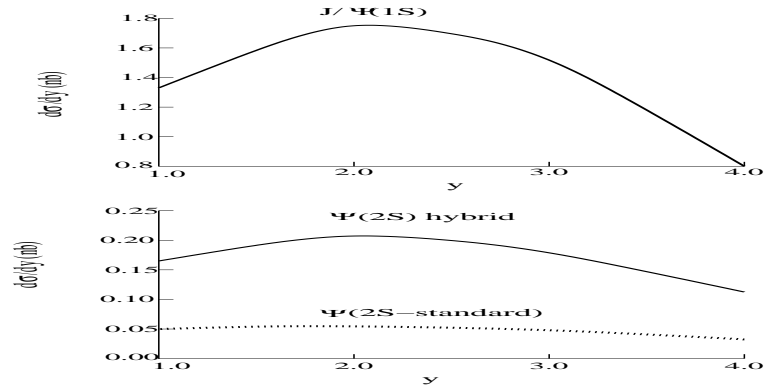


Figure 1: $d\sigma/dy$ for p-p collisions at $\sqrt{s} = 5.0$ TeV producing $J/\Psi(1S)$, and $\Psi(2S)$ for the standard model (dashed curve) and the mixed hybrid theory.

The differential rapidity cross sections for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ production for the standard model and the mixed hybrid theory for $E=5$ TeV are shown in Figure 2.

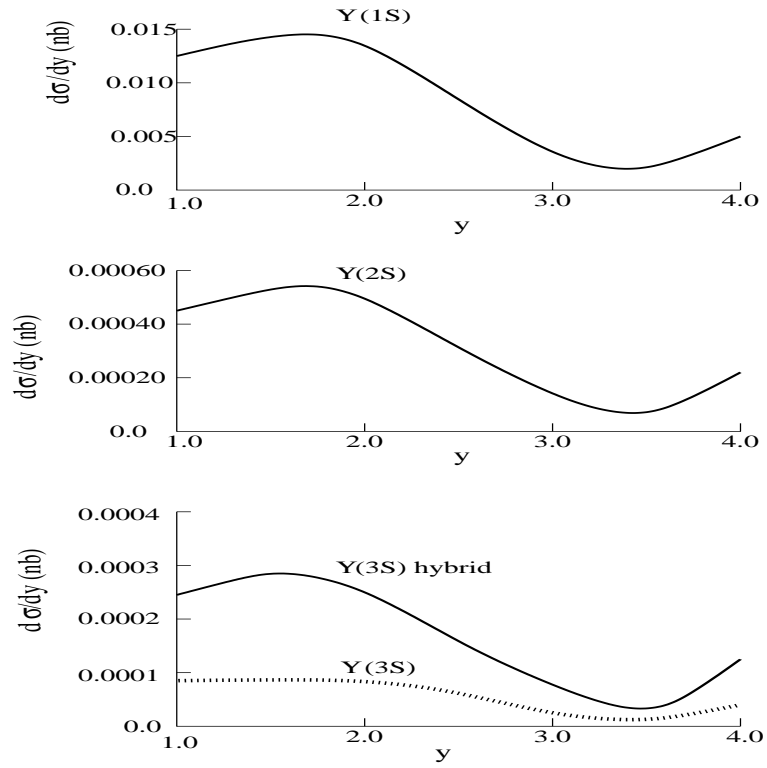


Figure 2: $d\sigma/dy$ for p-p collisions at $\sqrt{s} = 5.0$ TeV producing $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ for the standard model (dashed curve) and the mixed hybrid theory.

3 Differential Rapidity Cross Sections for J/Ψ , $\Psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ Production Via p-p Collisions at $E= 14$ TeV

For $J/\Psi(1S)$ production at 14 TeV $a = 1.15 \times 10^{-4}$ and $A_{\Psi(1S)} \simeq 1.59 \times 10^{-7}$ nb. For $\Psi(2S)$ production with the standard model $A_{\Psi(2S)} \simeq 0.039A_{\Psi(1S)}$, while with the mixed hybrid theory $A_{\Psi(2S)} \simeq 0.122A_{\Psi(1S)}$. For Υ production $a = 5.1 \times 10^{-7}$ and $A_{\Upsilon(1S)} \simeq 4.13 \times 10^{-9}$, while $A_{\Upsilon(2S)} \simeq 0.039A_{\Upsilon(1S)}$, $A_{\Upsilon(3S)} \simeq 0.0064A_{\Upsilon(1S)}$ for the standard model, and $A_{\Upsilon(3S)} \simeq 0.012A_{\Upsilon(1S)}$ for the mixed hybrid theory. With the parameters given above for $J/\Psi(1S)$ and $\Psi(2S)$ production, from Eq(1), $d\sigma_{pp \rightarrow \Psi(1S)}/dy$, and $d\sigma_{pp \rightarrow \Psi(2S)}/dy$ both for the standard model and the mixed hybrid theory for the $\Psi(2S)$ state are shown in Figure 3

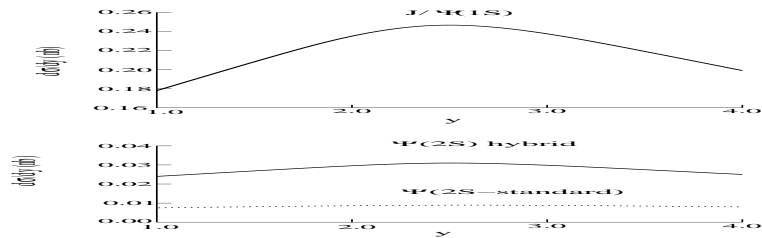


Figure 3: $d\sigma/dy$ for p-p collisions at $\sqrt{s} = 14.0$ TeV producing $J/\Psi(1S)$; and $\Psi(2S)$ for the standard model (dashed curve) and the mixed hybrid theory.

Similarly, with the parameters given above for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ both for the standard model and the mixed hybrid theory the differential rapidity cross sections for Upsilon production are shown in Figure 4. Note that as in Figures 1, 2 $d\sigma_{pp \rightarrow \Psi(2S\text{-standard})}/dy$ is much smaller than $d\sigma_{pp \rightarrow \Psi(2S\text{-hybrid})}/dy$ and that $d\sigma_{pp \rightarrow \Upsilon(3S\text{-standard})}/dy$ is much smaller than $d\sigma_{pp \rightarrow \Upsilon(3S\text{-hybrid})}/dy$.

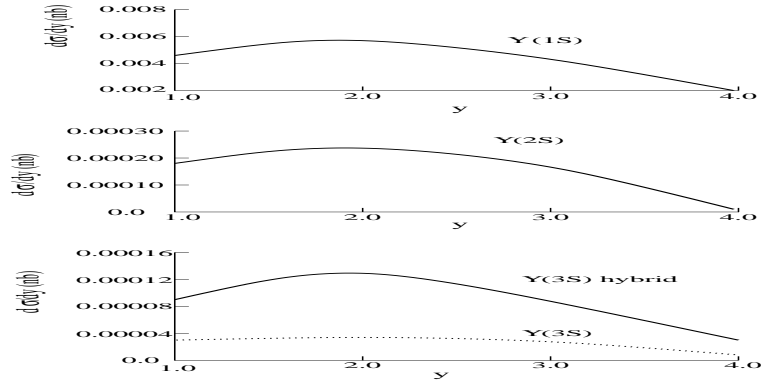


Figure 4: $d\sigma/dy$ for p-p collisions at $\sqrt{s} = 14.0$ TeV producing $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ for the standard model (dashed curve) and the mixed hybrid theory.

4 Ratios of Cross Sections for Ψ , Υ Production Via p-p Collisions Compared to Experiment for E=7 TeV

Because of problems with normalization we cannot compare our cross sections directly with experiment, but as in previous research a comparison of ratios of cross sections with experiment is an excellent test of the theory used to estimate Ψ and Υ production.

As discussed in an earlier publication[3] the estimated ratios for p-p production of $\Psi(2S)$ and $J/\Psi(1S)$ using the harmonic-oscillator wave functions for the standard model and a factor $\simeq \pi$ for the mixed hybrid theory are

$$\begin{aligned}\sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{standard} &\simeq 0.039 \\ \sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{hybrid} &\simeq 0.122 ,\end{aligned}\tag{6}$$

while the estimated $\Upsilon(2S)$, $\Upsilon(3S)$ to $\Upsilon(1S)$ ratios are

$$\begin{aligned}\sigma(\Upsilon(2S))/\sigma(\Upsilon(1S))|_{standard} &\simeq \sigma(\Upsilon(2S))/\sigma(\Upsilon(1S))|_{hybrid} \simeq 0.039 \\ \sigma(\Upsilon(3S))/\sigma(\Upsilon(1S))|_{standard} &\simeq .0064 \\ \sigma(\Upsilon(3S))/\sigma(\Upsilon(1S))|_{hybrid} &\simeq 0.0201 .\end{aligned}\tag{7}$$

4.1 Ratio of $\sigma_{\Psi(2S)}$ to $\sigma_{J/\Psi(1S)}$

Recently there have been measurements at E=7 TeV of the $\Psi(2S)$ to $J/\Psi(1S)$ cross section ratio by the CMS Collaboration[9], the LHCb Collaboration[10, 11, 12], and the ALICE Collaboration[13, 14]

The recent LHCb Collaboration[12] finds $\sigma_{\Psi(2S)} \times BR(2 \rightarrow \mu^+\mu^-)/\sigma_{\Psi(1S)} \times BR(1 \rightarrow \mu^+\mu^-) \simeq .02$, but since this result includes the $\Psi(nS) \rightarrow \mu^+\mu^-$ branching fractions it is difficult to compare to Eq(6). Similarly, the recent CMS Collaboration experiment[9] for the $\sigma_{\Psi(2S)}$ to the $\sigma_{J/\Psi(1S)}$ cross sections include the branching fractions, so these experimental result are difficult to test the theories shown in Eq(6).

From the recent measurements by the ALICE Collaboration[13] is

$$\frac{\sigma_{\Psi(2S)}}{\sigma_{J/\Psi}} \simeq 0.170 \pm 0.011(stat) \pm 0.013(syst) ,\tag{8}$$

one can see from Eq(8) that the $\sigma_{\Psi(2S)}/\sigma_{J/\Psi}$ ratio is much larger than the standard model and is consistent with the mixed hybrid theory[7] within theoretical and experimental errors.

The $\sigma(\Upsilon(3S))$ was not measured in Ref[13], so the ALICE experiment cannot be used for the important $\sigma_{\Upsilon(3S)}/\sigma_{\Upsilon(1S)}$ ratio to test Eq(7) for the standard vs the hybrid theory discussed in the next subsection.

Ψ and Υ production at 7 TeV was estimated in Ref[15], but no ratios were estimated.

4.2 Ratios of $\Upsilon(nS)$ Cross Sections

In this subsection we discuss the experimental $\sigma(\Upsilon(nS))$ ratios and possible comparison with our theory.

The $\Upsilon(2S), \Upsilon(3S)$ to $\Upsilon(1S)$ ratios at $E = 7$ TeV were recently measured by the CMS collaboration[16, 17], the LHCb Collaboration[18, 19], and the ATLAS Collaboration[20].

The experimental results for the $\Upsilon(2S)$ to the $\Upsilon(1S)$ and the $\Upsilon(3S)$ to the $\Upsilon(1S)$ ratios averaged over these three experiments are

$$\begin{aligned}\sigma_{\Upsilon(2S)} \times BR(2 \rightarrow \mu^+ \mu^-) / \sigma_{\Upsilon(1S)} \times BR(1 \rightarrow \mu^+ \mu^-) &\simeq 0.26 \\ \sigma_{\Upsilon(3S)} \times BR(3 \rightarrow \mu^+ \mu^-) / \sigma_{\Upsilon(1S)} \times BR(1 \rightarrow \mu^+ \mu^-) &\simeq 0.12\end{aligned}\quad (9)$$

From the recent Particle Data Group[21] $BR(1 \rightarrow \mu^+ \mu^-) \simeq 0.025$, $BR(2 \rightarrow \mu^+ \mu^-) \simeq 0.019$, and $BR(3 \rightarrow \mu^+ \mu^-) \simeq 0.022$. From this

$$\begin{aligned}\frac{BR(2 \rightarrow \mu^+ \mu^-)}{BR(1 \rightarrow \mu^+ \mu^-)} &\simeq 0.76 \\ \frac{BR(3 \rightarrow \mu^+ \mu^-)}{BR(1 \rightarrow \mu^+ \mu^-)} &\simeq 0.88 \quad \text{giving} \\ \sigma_{\Upsilon(2S)} / \sigma_{\Upsilon(1S)}|_{exp} &\simeq 0.34\end{aligned}\quad (10)$$

$$\sigma_{\Upsilon(3S)} / \sigma_{\Upsilon(1S)}|_{exp} \simeq 0.136 \quad (11)$$

From Eq(7) these ratios of Υ cross sections are too large for either the standard model or hybrid theory. Note however

$$\begin{aligned}\frac{\sigma_{\Upsilon(3S)} / \sigma_{\Upsilon(1S)}|_{exp}}{\sigma_{\Upsilon(2S)} / \sigma_{\Upsilon(1S)}} &\simeq 0.4 \quad \text{while} \\ \frac{\sigma_{\Upsilon(3S)} / \sigma_{\Upsilon(1S)}|_{hybrid}}{\sigma_{\Upsilon(2S)} / \sigma_{\Upsilon(1S)}} &\simeq 0.5 \\ \frac{\sigma_{\Upsilon(3S)} / \sigma_{\Upsilon(1S)}|_{standard}}{\sigma_{\Upsilon(2S)} / \sigma_{\Upsilon(1S)}} &\simeq 0.16 ,\end{aligned}\quad (12)$$

therefore the ratio of ratios are given by the hybrid theory within errors, while the standard model is too small.

4.3 Energy Dependence of Cross Sections

In this subsection we compare the experimental energy dependence of cross sections with our theory.

Note that A_Φ defined after Eq(1) has the property $A_\Phi(s) \propto 1/s$, so cross sections should also be $\propto 1/s$. Recently, LHCb measured experimental ratios at 7 and 8 TeV at forward rapidity for $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ production[22]. The theoretical and the experiment ratios are

$$\begin{aligned}(\sigma_{\Upsilon(8TeV)} / \sigma_{\Upsilon(7TeV)})_{theory} &\simeq 1.306 \\ (\sigma_{\Upsilon(8TeV)} / \sigma_{\Upsilon(7TeV)})_{experiment} &\simeq 1.291 \pm 0.005 ,\end{aligned}\quad (13)$$

so our theoretical ratio for different energies is consistent with experiment within errors.

5 Conclusions

Our results, shown in the figures, for the rapidity dependence of $d\sigma/dy$ for p-p collisions at 5 TeV are much larger than those estimated both at 14 TeV and 13 TeV[2], which is consistent with our prediction that $d\sigma/dy$ increases when the energy is decreased is consistent with experiment. The experimental results for the ratio of the $\Psi(2S)$ to $J/\Psi(1S)$ cross sections at E=7 TeV are seen to be consistent with the mixed hybrid heavy quark theory[7] and not with the standard model. For the ratio of the $\Upsilon(3S)$ and $\Upsilon(2S)$ to $\Upsilon(1S)$ cross sections one needs the branching fractions. We found that experimental ratios of both $\sigma_{\Upsilon(3S)}$ and $\sigma_{\Upsilon(2S)}$ to $\sigma_{\Upsilon(1S)}$ were too large for either the hybrid theory or the standard model, but the ratio of ratios was consistent with the hybrid theory.

In a test of the energy dependence of cross sections it was shown that for $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production the ratios for 7 and 8 TeV in our theory is consistent with experiment.

With the LHC data now collected for 5 TeV[1] and possibly in the future at 14 TeV our results should be useful for comparison with experiments. The result that $d\sigma/dy$ for the production of $\Psi(2S)$ and $\Upsilon(3S)$ is much larger with the mixed hybrid theory than the standard model is a test of the validity of the mixed heavy quark hybrid theory, which is very important since we are using the mixed hybrid heavy quark theory to test the creation of the Quark Gluon Plasma via RHIC experiments.

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